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Glider Optical Measurements and BUFR Format for Data QC and Storage

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ABSTRACT

Unmanned underwater vehicles are becoming an increasingly important platform in oceanographic research and operational oceanography, where continuous *in situ* sampling throughout the water column is essential to understanding the ocean circulation and related biological, chemical, and optical activity. The latter directly affects field operations and remote sensing capabilities from space. A unified approach is necessary for data quality control (QC), access, and storage, considering the vast amount of data collected from gliders continuously deployed across large areas and over long durations. The Binary Universal Form for the Representation of meteorological data (BUFR) maintained by the World Meteorological Organization (WMO) is adapted to include physical and optical parameters from a variety of sensor suites onboard underwater vehicles. The provisional BUFR template and related BUFR descriptors and table entries have been developed by the U.S. Navy for ocean glider profile data and QC results. Software written in FORTRAN using the ECMWF BUFRDC library has been implemented to perform both the encoding and decoding of BUFR files from and to Network Common Data Form (NetCDF) files. This presentation also discusses data collected from sensors on gliders deployed both in deep water and shallow water environments, including issues specific to optical sensors at various depths.

INTRODUCTION

One of the key obstacles in oceanographic research and operational oceanography is the difficulty associated with field sampling and measurements, due to lack of easy access to the vast areas of the ocean, that cover approximately 70% of the planet surface. Remote sensing techniques (both active and passive), especially those from space, have been proven to offer synoptic surface coverage with adequate accuracy, when sensors are calibrated and validated correctly with help from in situ measurements, while the effects of atmosphere are also estimated correctly. Even so, such signals are heavily weighted, thus biased, towards the features from the surface layer. Ocean circulation models offer much needed 3-dimentionality to the mix, allowing the described features extending beyond the surface layers, on top of the 2D synoptic coverage. With the initial boundary conditions properly determined, which can be obtained from *in situ* measurements and satellite observations, the models allow the 4th dimensionality, or forecast, be included in the framework.

Traditional ship-based ocean sampling techniques are still widely used today. Advances have been made in great stride recently by numerous *in situ* observation systems on moorings, buoys, floats, flow-through sensors, unmanned underwater vehicles (UUVs), such as gliders, autonomous underwater vehicles (AUVs), remotely operated Vehicles (ROVs), integrated sensor networks, and observatories. These are vibrant research and development areas and generate the most accurate three-dimensional (3D) data available, often in real-time, and are less affected by adverse conditions. However, spot sampling lacks the rapid, broad coverage that is critical in high-level, real-time operational decision making. *In situ* observations at times are not available for unsafe or denied-access environments. Remote sensing techniques can be used to fill the needs, when precise protocols are in place to maintain data coherence and accuracy. Further, modern defense and security needs demand that accurate information be provided when and where it is needed (e.g., Battlespace on Demand, BonD). Ocean sensing must not only provide timely and accurate data, but also offer insights regarding overall 3D and future – or forecasted-environmental conditions. The combined use of *in situ* observations, remotely sensed data, and physical models is a rapidly evolving field, although improved assimilation of

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available data into models still poses a challenge. The ability to sense, integrate, and predict is vital in establishing a true real-time, four-dimensional (4D) cube of verified and validated information for ocean nowcast and forecast, as shown in Figure 1, in terms of Tactical Ocean Data System (TODS). We see that glider observations provide critical input to one of the key elements in BonD tier 0 structure.

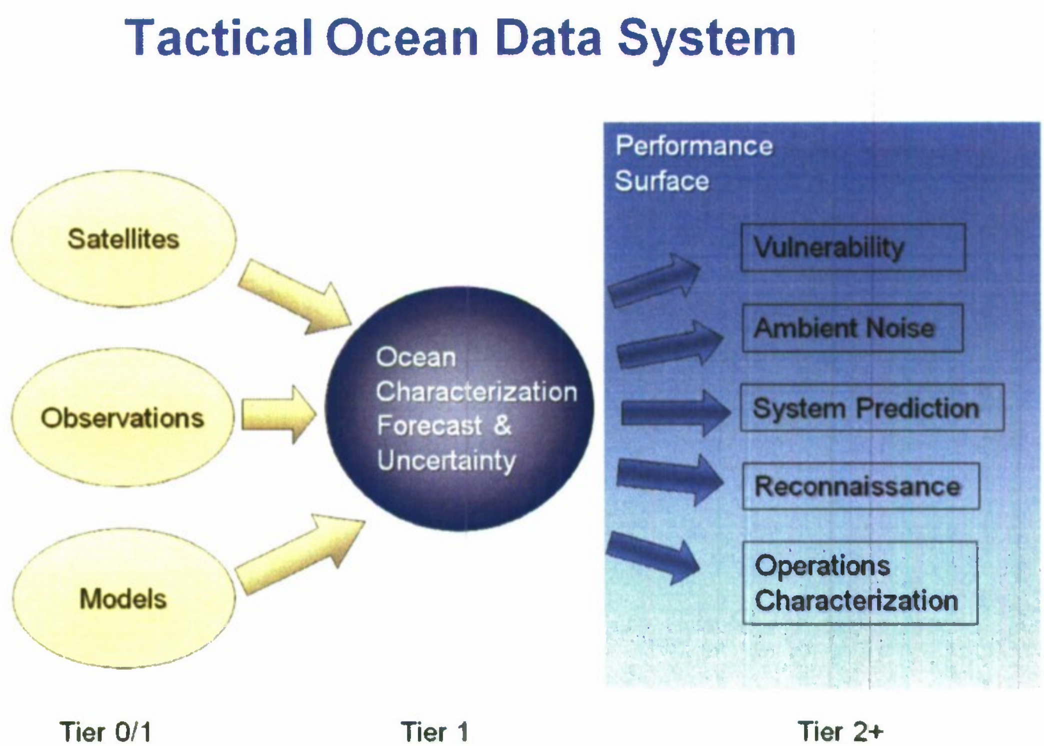

Figure 1. Tactical Ocean Data System (TODS) component chart.

Glider observations provide inputs that are not only limited to localized or spot events, but are also capable of long-range, long-term, in-depth throughout the water column. One good example is the recent 7-month voyage by a Rutgers University Slocum glider crossing the Atlantic Ocean, sampling the ocean structures along the way. The vast data stream generated by gliders contains a wealth of much needed information for topics discussed above. Automated QC and analysis of these data are the only way for the timely assimilation to models and the framework above.

This paper describes the capabilities of glider optical measurements at the Naval Research Lab (NRL) and the Naval Oceanographic Office (NAVOCEANO), and efforts associated with the development of automated optics QC processes and storage format.

GLIDER OPTICS MEASUREMENTS AND PROCESSING

To answer the needs of Mine Warfare (MIW), Anti-submarine Warfare (ASW), safety of navigation, monitoring global climate change, and battlespace environment sensing, optical sensors have been fitted and tested on different types of gliders, and have proven successful in assessing optical conditions in a variety of water masses. These sensors provide inputs for optimizing ocean optical models used to generate and forecast electro-optical identification (EOID) performance surfaces, diver visibility and asset vulnerability products, which can aid in tactical decision making during fleet operations (Figure 1).

Name	Description	Units	Typical value	Range	Resolution (step)	possible channel #s	Bandwidth (nm)	Instruments
bb	backscatter	m^{-1}	0.004	0~0.1	0.0001	<255	30	bb2f,bb3slo
Ed	Irradiance	wm^{-2}	10	0~500	0.1	<512	10	OCR504/7I (*)
c	beam attenuation	m^{-1}	0.2	0~100	0.01	<255	10	BAM (x)
b	Scattering	m^{-1}	0.1	0~100	0.01	<255	10	AUVb
vis	visibility	m	10	0.1~100	0.1	<255	-	AUVb,SAM, BAM
PAR	photo. avail. rad.	mEinstein m^{-2}	100	0~2500	1	<255	-	ECO-PAR (x)
Fl-chl	[Chlorophyll-a]	mg m^{-3}	0.5	0~100	0.01	470/695	10	bb2f,fl3
Fl-phyco	phycoerythrin	ppb	0.05	0~100	0.005	540/570	10	fl3
Fl-cdom	color dissolved	ppb QS	2	0~2000	0.1	370/460	10/70	bb2f,fl3

Table 1. NRL/NAVOCEANO glider optical parameters table.

An automated QC process for optical measurements from gliders is designed and implemented as part of the Local Automated Glider Editing Routine (LAGER) [1][2]. The optical algorithms are used to process data from available glider optical sensors (Table 1), including instruments that measure the beam attenuation coefficient (c), the total scattering coefficient (b), the backscatter coefficient (b_b), the fluorescence returns and thus derived concentrations of chlorophyll, *phycoerythrin*, and colored dissolved organic matter (CDOM), downwelling irradiance (E_d), phytosynthetically available radiation (PAR), and other derived optical parameters, such as diver visibility (Table 1). All current optical sensors, including the ECO series from Wetlabs (bb2f, bb2slo, fl3, SAM, BAM, AUVb, ECO-PAR), and OCR504/7 from Satlantic, are included in the current operational version, with flexibility built in to allow for expansion to meet future needs. Additionally, Table 1 outlines the typical range, resolution, bandwidth, and channel limits of the optical sensors, which are used in the LAGER Optics routines and will be discussed in later sections. The data flow can be viewed as a 5-step process, with the inclusion of optics, as shown in Figure 2. Notice that the process can be enabled such that all data will (1) be sent to manual editing, (2) undergo physical parameter processing only, or (3) undergo both physical and optical parameters processing.

Glider data ingest module reads in real-time raw data at the NAVOCEANO Glider Operation Center (GOC) and converts to Network Common Data Form (NetCDF) format. Automated QC is the key step in LAGER Optics. It uses flags to classify different types of erroneous data points, and the combined quality of the flags determines whether Manual User GUI (MUG) is needed for closer inspection. The resulting data are then sent to the database in a binary universal format for representing meteorological data (BUFR) format required by the real-time data handling system (RTDHS) at NAVOCEANO.

The automated optical QC program structure is shown in Figure 3. The detailed description of each module can be found in [2]. Briefly, QC tests for optical variables implemented in LAGER, follow certain algorithms and conventions for detecting and flagging bad data that were developed for processing the physical variables, such as the temperature (T), and the salinity (S). However, because of the multiplicity of optics variable types and frequency bands, a 2D variable array structure is used in contrast to the 1D vector approach used individually for T and S. The reader is referred to [1] for details of the physical data QC implementation. Two of the physical QC algorithms implemented in LAGER are used with minor adaptations for the Optics QC (OQC). These are the global bounds check and the spike test. The latter defines a spike to be a single datum departing significantly from its neighboring values (single-point spike). It has the additional feature of being able to detect such a spike in the presence of a gradient (as a function of depth) of the relevant hydrographic or optical variable. Since segments of anomalous optical data may span several data points, a method to detect these cases, in the form of a running standard deviation filter, is also included in the OQC. This filter finds and flags data that depart significantly in value from a local mean computed inside a 'running' window (depth interval) that is moved through the entire sampled depth range of the profile. In addition to the variable value range check, the depth of each sample point is also checked and 'chopped' short, if necessary, to eliminate values that appear to lie above, or too

close to the surface, where processes such as wind waves and bubbles could make optical measurements, such as backscattering and downwelling irradiance, either invalid or difficult to interpret reliably. If this depth is shallower than a given depth (default 1 m) or is negative, the variable value is flagged accordingly. A constant profile check is also done to determine if the values for a particular optics variable are constant throughout the sampled depth range, which was proven critical in assessing real-time electro-optical sensor performance, such as those during the RIMPAC 2008 exercise [3]. This might occur for a variety of reasons, such as instrument sampling faults, or sensor contamination, which suggest the data are invalid.

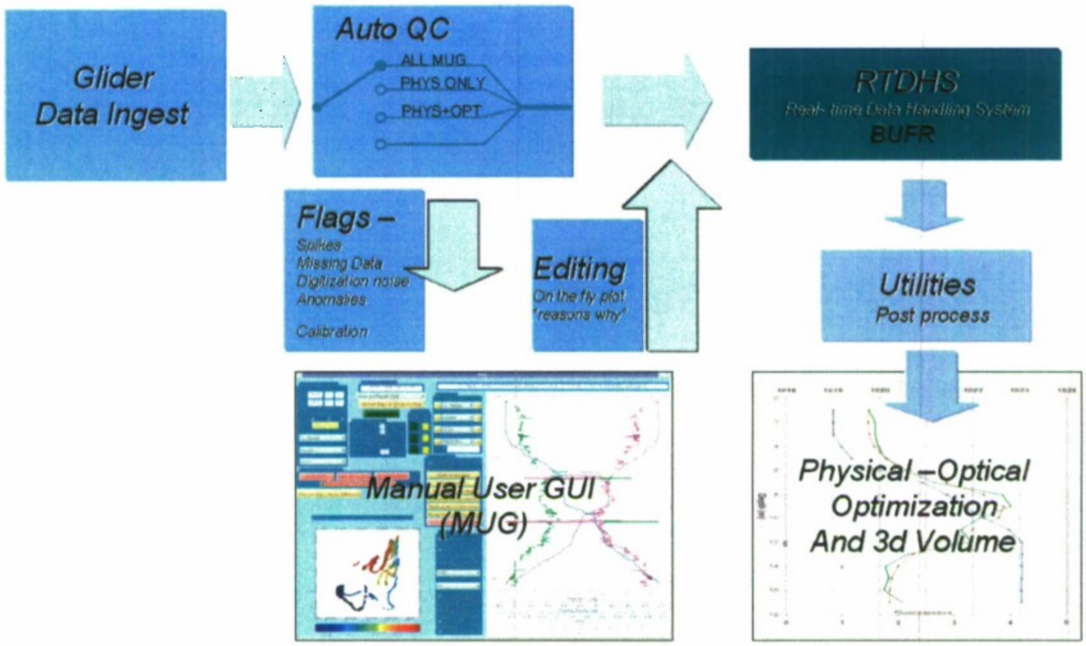

Figure 2. Data flow chart of LAGER Optics.

In the present LAGER optics algorithm, all the OQC tests are independent of geographic location and time of year, and the tests are also independent of depth, except in cases where different critical test values are used in two different depth ranges. The universal character of the tests weakens their capability to detect erroneous anomalies in specific regions. However, most of the parameters used to configure the OQC algorithms are stored in information files, and may be edited to adapt them manually, if necessary, to specific regions, or seasons. A future version of LAGER will include capabilities to adapt these parameters to specific regions automatically, based on a regional climatology or historical data, or alternatively, specific regimes, such as shallow or deep ocean settings, or proximity to the coast, and relationship to other physical parameters. This is particularly important for optical data, for which the dynamic range varies widely, depending upon the prevailing oceanographic setting or conditions. In highly productive, nutrient-rich regimes and/or close to estuarine freshwater sources, values of Chlorophyll-a and CDOM at the surface, or in the pycnocline, may reach highly-elevated values, and may exhibit very steep property gradients, that are not observed in deeper water.

For the physical variables, several glider-specific tests have been added to the OQC to detect and flag specific known types of bad behavior exhibited by either specific kind of gliders or by all types of gliders. In most cases, the glider-specific tests are functions of the vertical velocity of the glider that is employed as a substitute for the total speed of the glider through the water, which is difficult to determine. There are some early indications that similar provisions will need to be made for the optical data. However, insufficient data have been accumulated to clearly establish the need for such corrections and to reliably specify a remedial strategy.

Optical error flags are initially set to zero at each depth. Tests are performed on observed temperature and salinity values prior to any tests performed on optical values. If a test fails at a specified depth, then the corresponding flag is set to the failure flag value for that test at that depth. The flag values for corresponding test are listed below:

Flag name	assigned value
Global bounds check	2
Bb buddy check	4
Running STD check	5
Constant value check	6
Surface depth check	7

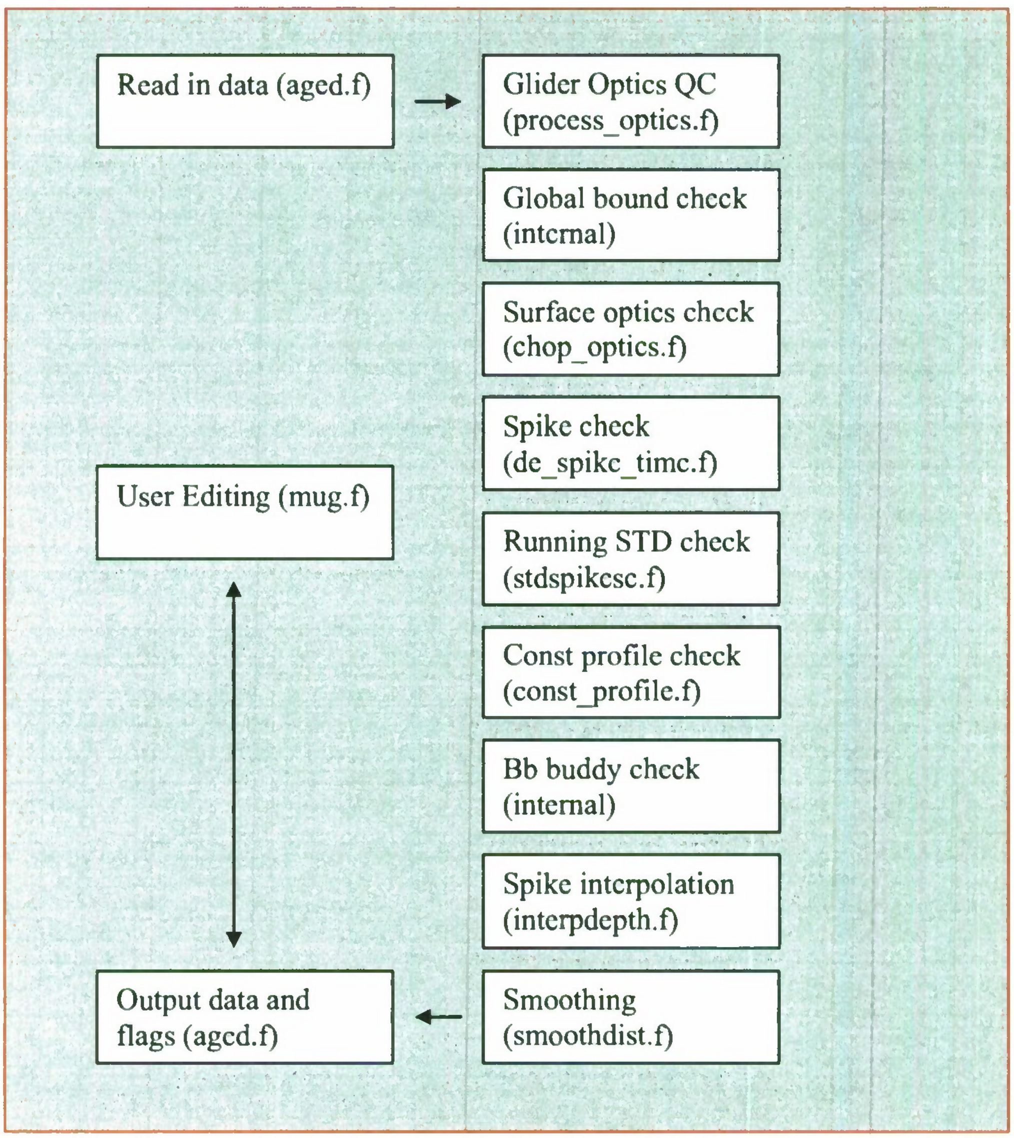

Figure 3. LAGER Optics V1.0 data quality check flow chart.

The LAGER OQC sends a multi-sensor multiple-band optics file for further evaluation in the manual QC step if, for any of the individual profiles in the file, the number of profile observations flagged as bad is greater than a given percentage (default 15% for the current configuration) of the total number of observations of that profile. It is planned to examine additional criteria to determine if the quality of the profiles on the basis of the temperature and salinity or optics variable values. (See [1] for details concerning the corresponding criteria for the physical data). Hence, a file may be sent to manual QC because either or both of temperature or salinity require editing or deletion, or because at least one of the optical profiles requires visual inspection. In addition, an individual T, S, or optical variable profile may be flagged for deletion if the number of bad data, or gaps, are excessive. A needs_manual_editing_flag is assigned in each file to each ascending or descending profile (each value summarizes quality of the corresponding optics variable profile).

GLIDER OPTICAL TABLE AND ADAPTED BUFR

To meet automated data QC, downstream model requirements and archive needs, BUFR format is adapted from meteorological research to be used at the NAVOCEANO GOC. All glider sensor outputs including temperature, salinity and various optical parameters are examined and converted in BUFR data tables. Details of such tables can be found in [4]. BUFR has been used since 1989 for data archive and maintained by the World Meteorological Organization (WMO), which is described in details at the following website: http://www.wmo.ch/pages/prog/www/WMOCodes/OperationalCodes.html. Briefly, a BUFR message contains 6 sections (0-5) to store header and data. Section 3 contains a short header followed by data descriptors which defines the form and content of the bit-stream in Section 4. The sequence of descriptors in Section 3 could be viewed as the template of the BUFR message. This template contains the information needed to describe the structure of the data values embedded in the matching bit-stream in the following section (Section 4). The template is to be interpreted in a step-by-step, algorithm-like manner. Given a set of BUFR messages, the values contained in the bit stream in Section 4 may differ from one message to the next corresponding to different glider profiles, but their ordering and structure will be kept predictable if the template provided in Section 3 remains unchanged. The NRL/NAVOCEANO optics table (Table 1) has been designed and incorporated into NAVOCEANO BUFR tables, with an assigned Class 60 descriptor (Table 2). The optical variables QC flags corresponding to Table 1 are shown in Table 3.

F	X	Y	Scale	Reference Value	Bit Width	Unit	Description
0	60	001	4	0	10	m^{-1}	Backscatter
0	60	002	1	0	9	wm^{-2}	Irradiance
0	60	003	2	0	14	m^{-1}	Beam Attenuation
0	60	004	2	0	14	m^{-1}	Scattering
0	60	005	1	0	10	M	Visibility
0	60	006	0	0	12	mEinstien.m^{-2}	Photosynthetic Avail. Radiation
0	60	007	2	0	14	mg/m^3	Chlorophyll-a
0	60	008	3	0	17	Ppb	Cyanobacteria
0	60	009	1	0	15	Ppb	Color Dissolved
0	60	010	0	0	10	Nm	Center Wavelength
0	60	011	0	0	7	Nm	Bandwidth
0	60	012	0	0	96	CCITT_IA5	Instrument

Table 2. BUFR optics Table (class 60), adapted from the optics parameters listed in Table 1.

Traditional optical variable names and units are used. Typical values listed are adapted from open ocean or clear water environments. Bandwidth parameters are from current or past instruments tested on a variety of ocean gliders, with names denoted from raw data stream. The spectral information is not listed in this table and is subject to change, depending on individual sensors onboard gliders. Multiple wavelengths of certain sensors (e.g. bb3slo) should be expected and have been implemented in the BUFR table by means of repetition.

The above automated QC routines are in place and have been tested under different conditions, using data from different types of gliders. The results show [3] that under the most complicated situations involving complexities associated with data transmission as well as environmental variability, as much as 30% of profiles require manual examination by operators. The failure rate in detection of bad profiles is less than 0.4% of the profiles examined, which is associated with sparseness of the data, and single point spikes likely due to subsurface optical layers.

F	X	Y	Scale	Reference Value	Bit Width	Unit	Description
0	63	001	0	0	4	Code Table	Automated QC Flags – Temperature
0	63	002	0	0	4	Code Table	Automated QC Flags – Salinity
0	63	003	0	0	4	Code Table	Manual QC Flags – Temperature
0	63	004	0	0	4	Code Table	Manual QC Flags – Salinity
0	63	005	0	0	4	Code Table	Full Profile QC Flag - Temperature
0	63	006	0	0	4	Code Table	Full Profile QC Flag – Salinity
0	63	007	0	0	6	Code Table	Automated QC Flags – Optics
0	63	008	0	0	4	Code Table	Manual QC Flags – Optics
0	63	009	0	0	4	Code Table	Full Profile QC Flag – Backscatter
0	63	010	0	0	4	Code Table	Full Profile QC Flag – Irradiance
0	63	011	0	0	4	Code Table	Full Profile QC Flag – Beam Attenuation
0	63	012	0	0	4	Code Table	Full Profile QC Flag – Scattering
0	63	013	0	0	4	Code Table	Full Profile QC Flag – Visibility
0	63	014	0	0	4	Code Table	Full Profile QC Flag – PAR
0	63	015	0	0	4	Code Table	Full Profile QC Flag – Chlorophyll-a
0	63	016	0	0	4	Code Table	Full Profile QC Flag – Cyanobacteria
0	63	017	0	0	4	Code Table	Full Profile QC Flag – Color Dissolved

Table 3. Quality control class (63). See text for details.

SUMMARY

Glider optical measurements provide critical input to establish an accurate optical ocean sensing and forecasting system, that fuses observations from satellite remote sensing sensors and outputs from ocean circulation models. Together, a 4D verified data cube can be utilized in real-time operational decision making. An automated glider optics QC package is needed to handle the large volume of input data, while it outputs much needed information for downstream optical products, including 3D structure optimization and performance surface predictions for electro-optical identification (EOID) sensors. Extension testing has been implemented and results show a low level failure rate, which can be further improved once current development algorithms are incorporated.

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